APPENDIX G
TECHNOLOGY IDENTIFICATION USING THE ANALYTICAL HIERARCHY PROCESS

The potential size of a future technology deployment analysis is large, and efforts to assess the potential for GHG mitigating technologies will necessarily be limited by time and resources. This section describes a process for reducing the scope of such a study by identifying the most promising technologies up-front in a manner that is consistent, flexible, promotes consensus-building among analysts, and permits the treatment of both quantitative and qualitative inputs. After a shorter list of technologies is developed, these can then be assessed in a more detailed manner, whether it be a detailed optimization model, or more simple techniques such as the exogenous construction of deployment scenarios.

Such a process has been developed by the National Renewable Energy Laboratory (NREL) and applied to Mexico in a recent case study (Corbus, et al. 1994). The methodology, shown in Figure G-1, can be described as a "funneling" process by which a short list of technologies is identified out of a larger group of possibilities. As the analyst steps through this process, the tools for assessing each technology become more rigorous, while the list of technologies becomes shorter. The figure describes a four-step process in which a list of technologies is screened, that list is further refined (according to the Analytical Hierarchy Process, or AHP), deployment scenarios are developed, and specific near-term projects identified. Although the deployment scenarios and project identification are useful tools for analyzing technologies for developing countries, this section will focus on the first two steps, technology screening and evaluation (using the AHP), as a means of identifying key technologies that can be further assessed using a wide range of analytical tools, including those listed in Figure G-1.

Technology Screening

The goal of the Mexico case study was to use the methodology to identify promising renewable energy technologies for Mexico that would satisfy future energy needs while, at the same time, reducing carbon emissions. At the start of the project, more than 60 renewable energy technology/end-use combinations were defined as technically feasible in Mexico. The first task was for the NREL analysts to work with in-country energy experts to develop a reduced list of technologies for more detailed assessment. This screening process identified 13 technologies out of the 60 that met several criteria, specific to the study's goals.[1] These criteria were developed by the study team to reflect the project goals; however, any set of factors can be applied. Of particular importance for GHG mitigation studies is the size of the energy market that can be penetrated by renewables. For example, in Mexico the off-grid electricity demand is estimated to be 4% of the total

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[1] These are: biomass cogeneration, mass burn of municipal solid waste (MSW), micro/mini hydropower, biomass direct combustion, biomass gasification/gas turbine, wind, solar photovoltaics, solar thermal, and geothermal for on-grid electricity production. For the transportation sector, the following were studied: ethanol, methanol (from natural gas), compressed natural gas (CNG), and methanol (from biomass). Although not renewable, CNG and methanol from natural gas were considered since they are promising alternative fuel options for the near- to mid-term.

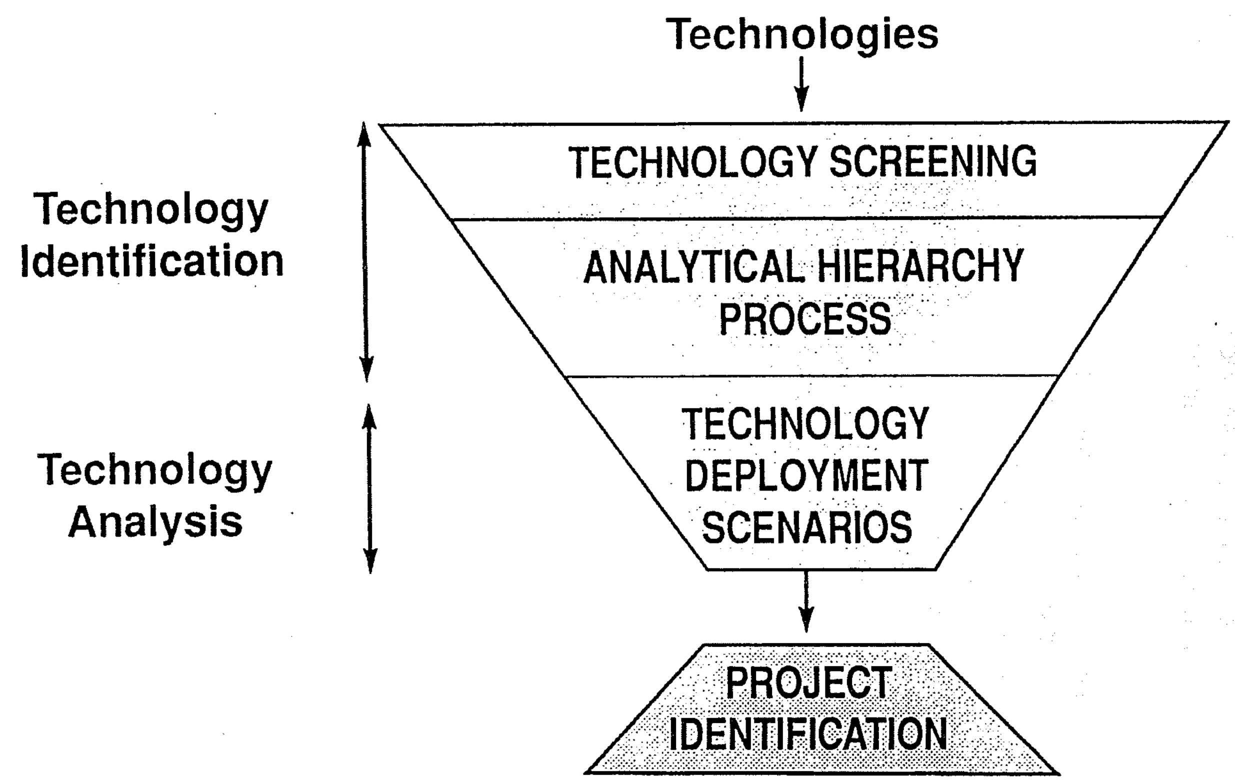
Technologies
TECHNOLOGY SCREENING
ANALYTICAL HIERARCHY PROCESS
TECHNOLOGY DEPLOYMENT SCENARIOS
PROJECT IDENTIFICATION
Technology Identification
Technology Analysis

Figure G–1

electricity requirements (the rest being on-grid) and is expected to decrease in the future (Corbus, Mark, and Martinez 1993). As a result, 100% penetration of the off-grid market by renewables could only reduce fossil energy use (and concomitant GHG emissions) by a maximum of 4%. Given the focus of the project, GHG reductions, off-grid renewable electric technologies were excluded as a result of the technology screening activity, even though these markets are particularly attractive for their near-term, high value, and social development attributes. Clearly, off-grid renewable technologies have a much more important role to play in those countries where the off-grid market is much larger.

The technology screening activity is centered around the assumption that the scope of the analysis can be efficiently reduced up front based on inputs from energy experts. In the Mexico project, relatively little time was spent reducing the list of technology options to the 13 used for further study; however, considerably more detail and scrutiny can be used if deemed necessary. The efficiency of the next step, the AHP, however, is markedly reduced if a large number of options need to be considered at once.

Technology Evaluation (AHP)

The AHP provides a methodology to rank technologies for end uses in terms of specific criteria that may be quantitative (such as specific cost data) or qualitative (such as the social acceptance of a given energy technology). The AHP is a decision analysis tool based on the work of Saaty (1980) that breaks down the constituents of a problem into parts and allows comparisons and rankings of these criteria. These comparisons in turn allow calculations of the weights or priorities of the different parts and overall priorities to evaluate (in this case) the list of potential technologies. The AHP has found widespread use in a variety of decision analysis applications, including some recent energy analyses. For example, Hamalainen used the AHP to evaluate the role of nuclear energy in Finland (Hamalainen 1990; Hamalainen 1991), and Tzeng, el al. (1992) used a version of the process for evaluating energy options in Taiwan.

Because the AHP involves selecting and assessing criteria in terms of larger goals (in this case, reducing carbon and other greenhouse gas emissions while meeting desired energy, economic, and social ends), the process will involve some subjective decision making by analysts. The AHP provides a comparative methodology that allows selecting, ranking, and applying any number of criteria considered important by the participants. Because only *relative* comparisons of the different criteria are being made, detailed data are not always necessary, and data requirements are not burdensome. The method can be applied across all energy end-use sectors or limited to key end-use sectors or sub-sectors, for example, transportation and on-grid electricity (as applied in the Mexico case study).

As used in the Mexico study, the AHP hierarchy consists of three levels (see Figure G-2). Pairwise comparisons of elements in the second level of the hierarchy are made with respect to the overall objective of the problem, which is given in the first level of the hierarchy. For example, the relative importance of cost versus resource availability for the penetration of renewable energy technologies (RETs) (and concomitant GHG reductions) is established. The process of comparing elements in each level is then continued throughout the hierarchy (i.e., between level two and three).

From these pairwise comparisons, matrices containing the priorities of different combinations of comparisons are generated that identify the relative importance of each element in achieving the overall study goal. For example, the costs of Technology 1 and Technology 2 are compared in a pairwise manner, and these results feed into their overall ranking based on the relative weight of cost versus other criteria shown in level 2 (see Figure G-2).

Evaluation Criteria

The first step in the application of the AHP is to select criteria to evaluate the technologies. Criteria used in the Mexico study included weighted cost value (combining life-cycle and capital costs for a technology), resource availability, social acceptance, state of development, environmental impact, and infrastructure requirements. These are described below, and specific examples are taken from the Mexico study to demonstrate their application.

Weighted Cost Value

As part of the AHP, a weighted cost value was used to investigate several key economic parameters. The weighted cost value takes four cost parameters -- current, midterm (year 2010), and future (year 2025) life cycle costs, and near-term (year 2000) capital costs -- and combines them, along with a series of weighting factors, in a linear equation that provides a single number for each technology (called the weighted cost value).

The life cycle cost for each technology was determined from the literature. Although life cycle cost estimates inherently include capital costs, capital costs (c. 2000) were included as a separate technology parameter in the weighted cost value. The upfront capital outlays for a project, especially in a developing country such as Mexico where capital for large-scale energy projects can be scarce and the government's foreign debt is extremely high, are an important part of the overall investment criterion for a project. The capital costs ($/kWh) used in the weighted cost value are based on a typical size project for the given technology.

The use of the weighted cost value as an input to the AHP allows quantitative indicators of technology characteristics to be included in the subjective decision-making process represented by the AHP. By combining multiple technology parameters into one value, several characteristics can be considered without complicating the AHP by adding too many parameters.

In the Mexico study, the 13 different technologies were evaluated in terms of the weighted cost value criterion. Geothermal, biomass cogeneration, wind, and micro/mini hydro received the highest ranking for the on-grid analysis; CNG and methanol from natural gas for internal combustion engine vehicles received the highest ranking for the transportation category. It should be noted that average estimates were used for the weighted cost value and that costs are approximate and are based on technology goals; specific costs may vary for a given technology.

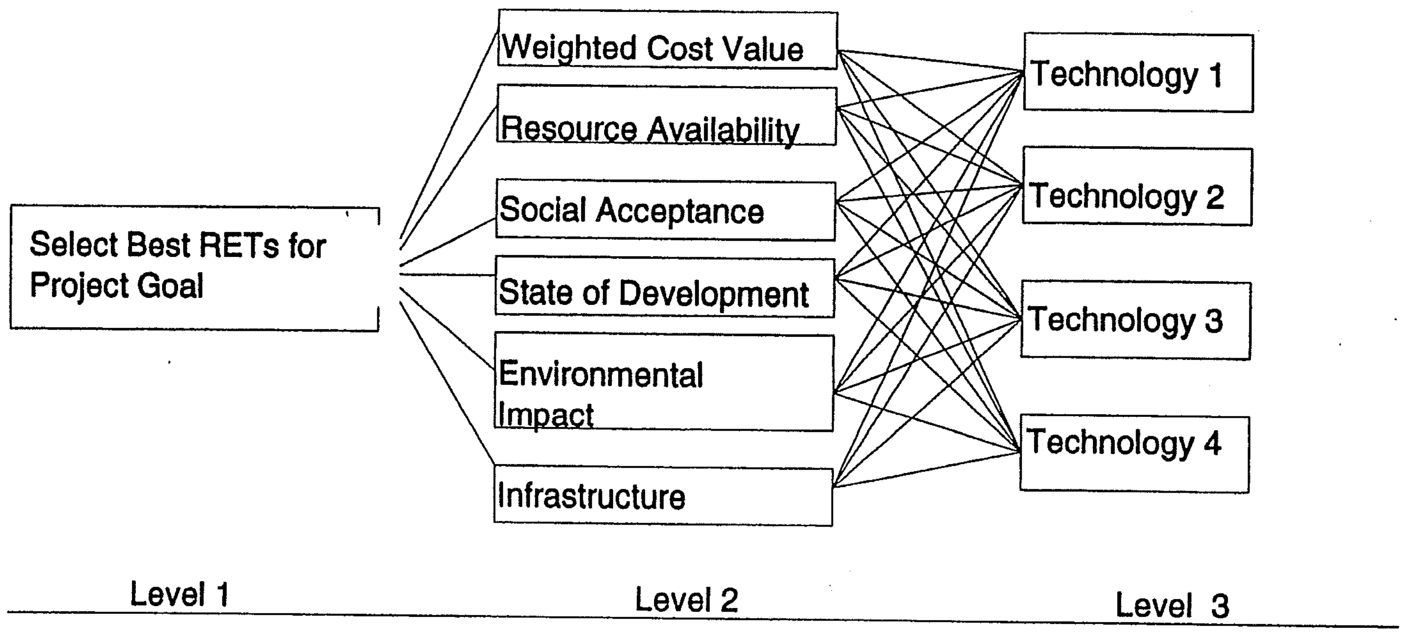
Select Best RETs for Project Goal
Weighted Cost Value
Resource Availability
Social Acceptance
State of Development
Environmental Impact
Infrastructure
Technology 1
Technology 2
Technology 3
Technology 4
Level 1
Level 2
Level 3

Figure G–2

Resource Availability

The resource availability for a given RET, including the quantity and quality of the resource, has a direct effect on the energy output of a RET and can be a determining factor in the economic feasibility of a RET in a given region. A large resource availability for a technology indicates potential for a large technology penetration, assuming that other technology deployment factors (i.e., other criteria considered in this analysis) are attractive. For the level of detail required for the technology identification process, resource availability on an aggregate national level is acceptable, although it should be noted that resource availability is extremely regional, and any evaluation of national resource availability is a generalization. In fact, resource availability for a given technology could be small in Mexico as a whole but extremely attractive in certain areas.

As is the case with many countries, available renewable energy resource data for Mexico are lacking in many areas. In general, resource availability for solar technologies was very high (Estrada and Barron 1991) as was the availability of wind (Elliot 1993) and biomass resources (Strategies Unlimited 1987) (based on the limited resource data available); projections of hydro and geothermal resources were based on government planning studies (SEMIP 1990).

Social Acceptance

Social acceptance includes both labor requirements and acceptance of the conversion technology. In general, existing systems are given a higher value because people are already familiar with them. This was particularly true for the transportation category because this sector requires a high degree of user interface with the energy service. Utility-generated electricity (i.e., on-grid), on the other hand, does not require the *user* to interface with a new energy system. However, *utility* acceptance of RETs, particularly with respect to power stability and intermittent constraints, is important but is considered under the infrastructure criterion.

The potential for a technology to create jobs in Mexico, for both operation and maintenance of a technology as well as manufacturing and installation, is considered an important component of social development. The impact of land use requirements for a given technology is also considered under this criterion to the extent that it has an effect -- perceived or real -- on displacing valuable land with alternative uses, such as farmland.

Existing technologies, such as direct biomass combustors or cogeneration systems, were given high rankings. Similarly, in the transportation category liquid fuels (e.g., methanol and ethanol) were favored over CNG because of their consistency with existing fueling modes for gasoline. In the case of dedicated biomass crops, the use of land for energy crops can compete directly with the use of the same land for food crops; as a result, crop residues were primarily considered in the analysis of biomass technologies. Crop residues can also impact the local transportation infrastructure, but this was evaluated under the infrastructure criterion.

State of Development

The following five categories were used to define a technology's existing state of development -- (1) research: from basic principles to laboratory models; (2) demonstration: when technical feasibility has been shown, and economic feasibility is sought; (3) mature: the technology has economic feasibility under restricted conditions; (4) commercial: the technology is available and has been demonstrated to be economically viable; and (5) massive: the technology has penetrated the market and is a major contributor.

State of development affects a technology's penetration rate because a technology cannot be significantly deployed until it reaches the commercial phase. In general, technologies with a low state of development will start to penetrate the market later than a technology with a high state of development (all other factors equal) and will therefore have smaller near to mid-term impact on GHG mitigation. Particular attention was paid here to technologies that are mature or commercial today but that also have advanced derivatives that offer enhanced operational or economic benefits in the long-term. A good example is biomass cogeneration technologies, which are currently deployed on a "massive" scale, but for which advanced gasification/gas turbine technologies that are currently in the research and demonstration phases may offer great long-term opportunities.

Biomass cogeneration and geothermal were considered massive technologies at present; wind, micro-hydro, and biomass direct combustion were considered commercial technologies. In the transportation category, ethanol from biomass was considered a massive technology as a result of the ethanol-from-sugarcane process that is carried out in Brazil. Both CNG and methanol from natural gas were considered commercial.

Environmental Impact

This consists of ranking the technologies based on environmental considerations, including non-GHG air emissions, water emissions, and land use. The environmental criterion receives a low priority for the *on-grid* category because the majority of RETs considered all have low environmental impacts. Since the project goal is the identification of *RETs,* as opposed to all energy technologies, the difference in environmental impacts is relatively small (e.g., all RETs result in a significant reduction in carbon emissions). However, the environmental criterion receives a high ranking for the *transportation* category because of the benefits in urban air quality associated with alternative transportation technologies.

For the electricity-producing technologies, mass burn of municipal solid waste and biomass direct combustion received the lowest ranking because of the air emissions associated with their use. CNG was favored over ethanol and methanol fuels because of its lower carbon monoxide emissions and smog-producing hydrocarbons, even though its emissions of nitrogen oxides were higher.

Infrastructure

This includes the distribution systems for the end-use energy as well as the collection systems for the fuel. Also included under infrastructure for the on-grid category is whether a technology is intermittent or dispatchable. Utilities can count on dispatchable technologies for power at any time (with the exception of unplanned outages); however, they cannot always count on intermittent technologies because of variations in the resource, although utilities may have a good idea of when the resource, and hence power output, is usually available. In general, dispatchable technologies are favored over intermittent technologies because they are not subject to the intermittent constraints of the resource.

Biomass resources, by their nature, have a very low energy density as compared to conventional fuels, hence the volume of resource needed for energy production is much larger than that of conventional fuels (e.g., coal). The low energy density of biomass restricts the distance that the resource can be economically transported. This can confine biomass energy production to the proximity of the resource, and can restrict technology size due to the economics of recovering large quantities of a resource. Therefore, the accessibility of the biomass resource can largely determine its use. This could be a significant factor in Mexico, where biomass resources may be located in areas without easy access, and where the infrastructure requirements for transport of biomass can be important.

Dispatchable RETs, such as geothermal, were favored over intermittent technologies, except in the case of biomass, where fuel collection was an important requirement. Natural-gas-based transportation fuels (CNG and methanol from natural gas) were favored over biomass fuels (e.g., ethanol and methanol from biomass) because of the existing infrastructure for natural gas production. In addition, liquid fuels were favored over CNG because of their consistency with the existing fueling infrastructure for liquid fuels.

Composite Priorities

The last step in the AHP is to establish composite, or overall, rankings for the RETs by using matrix multiplication to combine the local priority vectors resulting from the pairwise comparisons of level two and level three (see Figure G-2). Figure G-3 shows the relative weights of the six evaluation criteria used in the Mexico case study, demonstrating the relative importance of each criteria for both the on-grid electricity and transportation sectors. Based on the comparisons between each technology for these six criteria, composite rankings are then calculated, as shown in Figure G-4 for the on-grid technologies. The results of the AHP can then be used to identify those key technologies for which further, more detailed analysis is warranted.

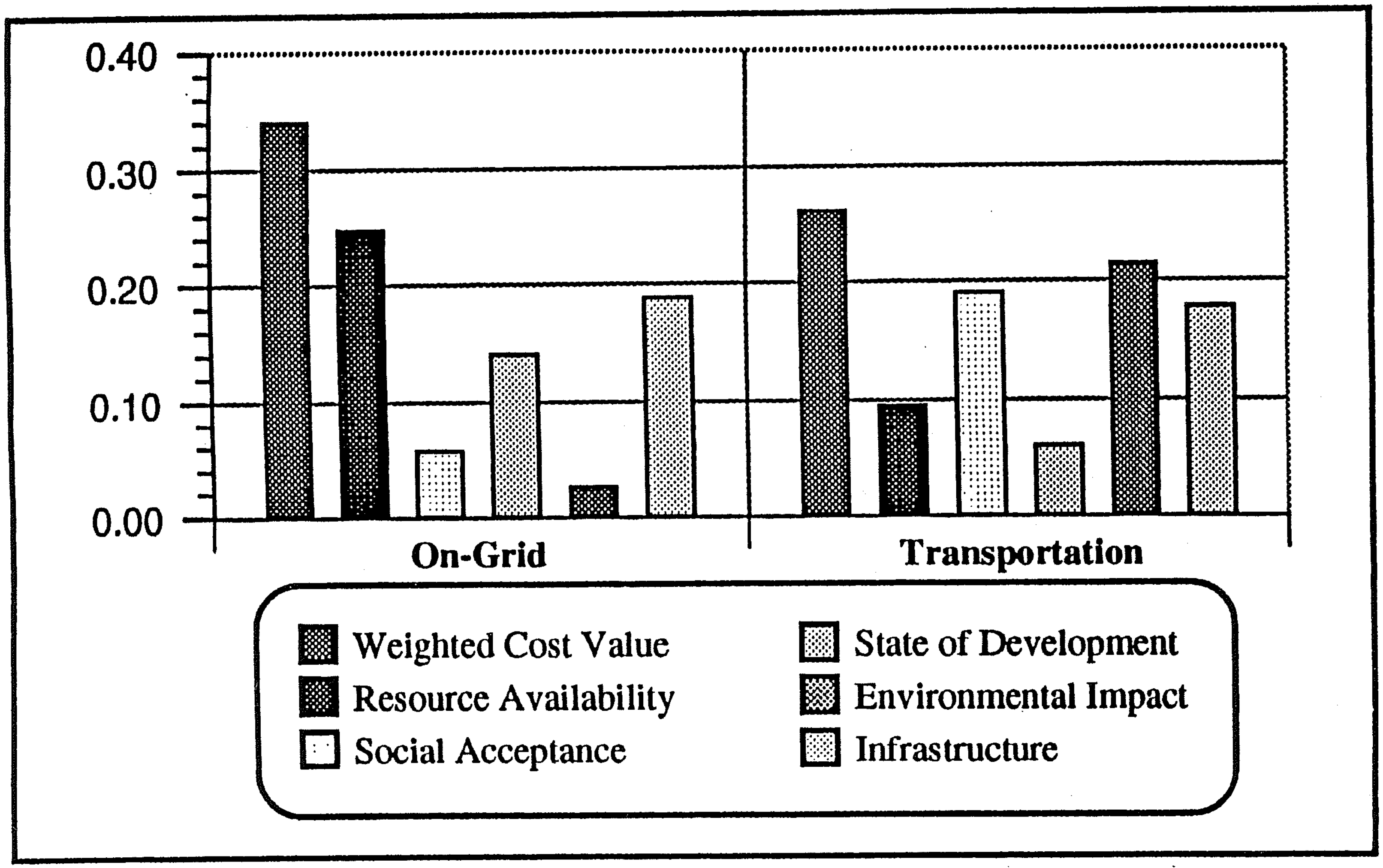
0.40
0.30
0.20
0.10
0.00
On-Grid
Transportation
Weighted Cost Value
Resource Availability
Social Acceptance
State of Development
Environmental Impact
Infrastructure

Figure G–3

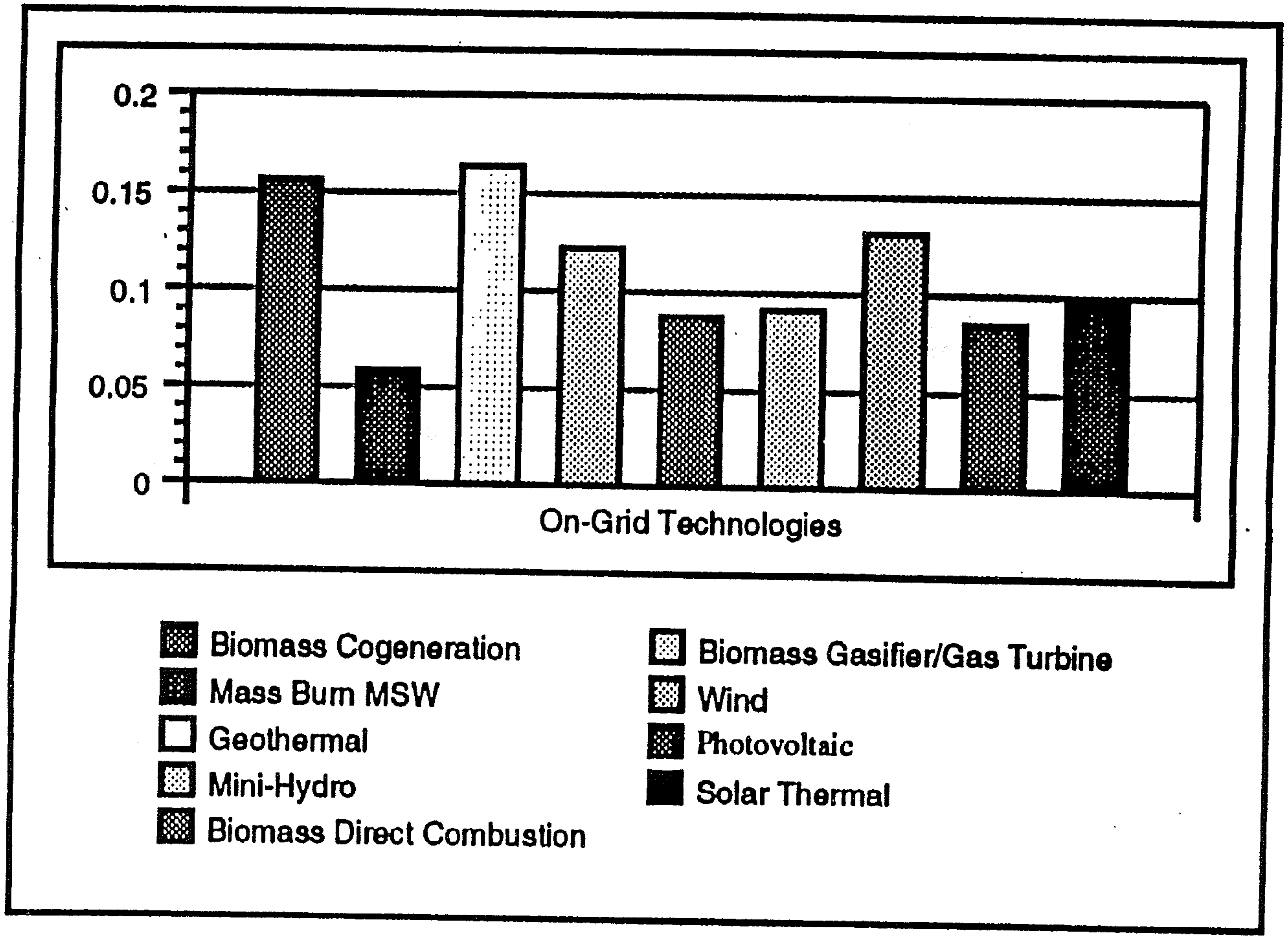
0.2
0.15
0.1
0.05
0
On-Grid Technologies
Biomass Cogeneration
Mass Burn MSW
Geothermal
Mini-Hydro
Biomass Direct Combustion
Biomass Gasifier/Gas Turbine
Wind
Photovoltaic
Solar Thermal

Figure G–4

REFERENCES

Corbus, Mark, Martinez, and Rodriguez. (February 1994). *Renewable Energy and Its Potential for Carbon Emissions Reductions in Developing Countries, Methodology for Technology Evaluation: Case Study Application in Mexico.* Golden, CO: National Renewable Energy Laboratory. Review DRAFT.

Corbus, Mark, and Martinez. (September 1993). "Renewable Energy Technologies for Mexico: Assessing Carbon Emission Reductions," *World Resources Review.* Volume 5.3.

Elliot, D. (1993). Personal communication with Dennis Elliot of Pacific Northwest Laboratories.

Estrada, Ignacio; Barron, Mauro (1990). *Mexico - Atlas de Radiacion Solar,* Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico.

Hamalainen, Raimo, (1990). "A Decision Aid in the Public Debate on Nuclear Power," *European Journal of Operations Research,* Vol. 48, 66.

Hamalainen, Raimo, (1991). "Facts or Values - How Do Parliamentarians and Experts See Nuclear Power," *Energy Policy,* Vol. 48, 464.

Saaty, T.L. (1980). *The Analytical Hierarchy Process.* New York: McGraw-Hill.

SEMIP (Secretaria de Energia Minas e Industria Paraestatal) (1990). *Programa Nacional de Modernizacion Energetica 1990-1994,* SEMIP, Mexico City, Mexico.

Strategies Unlimited (1987). *Renewable Energy Resources Market Analysis of the World.* Prepared for the California Energy Commission, California.

Tzeng, Gwo-Hshiung; Shiau T.; and Lin C; (1992). "Application of Multicriteria Decision Making to the Evaluation of New Energy System Development in Taiwan" *Energy - The International Journal,* Vol. 17, 983.